

# MODEL-BASED COMMISSIONING METHODOLOGY FOR SIMPLE DUCT SYSTEM

**Takao Odajima, Manabu Takashi, Björn Juckel-Murakami**  
*Design Department Takenaka Corporation, Tokyo, Japan*

## Summary

This paper presents how a simulation model is applied on air leakage and pressure distribution in a duct system and how it is utilized for duct system commissioning on the three categories below. It focuses on a duct system, which participates in room pressure differential control in higher functional facilities such as a pharmaceutical factory. For an air distribution system with room pressure control, an FTA (Fault Tree Analysis) analyses the main functional fault factors, which are classified into three categories. (I) Excessive air leakage from the duct system (II) Excessive pressure loss of the duct system. (III) The VAV characteristic does not match the characteristic of the duct system.

Keywords: commissioning, duct system, air leakage, pressure loss, VAV

## INTRODUCTION

The basic function of the duct system is to distribute the air properly. In other words, it is to provide the designed amount of air in the designed condition without wasting energy.

Commissioning of the duct system might not be necessary for residential or for general office type buildings, which mainly require control of room temperature and humidity only. However, for manufacturing, research or laboratory type facilities, where constant air volume and room pressure differential control with adjacent rooms is required, the duct system has an influence on the air changes, cleanliness and room pressure, besides above. This again will have an impact on the required performance.

Therefore it is important to have a proper method of commissioning on the duct systems in higher functional facilities.

In comparison with the commissioning process for a simple duct system in an office type building, the commissioning process of a laboratory type facility is more complicated.

The main objects of the duct system commissioning using models are as follows.

(a) Verification of the duct air tightness. (b) Verification of static pressure loss on the duct.

Generally, the above-mentioned objects are easy to be recognized as necessary. However, to determine proper and sufficient objects for duct commissioning, functional fault factors are identified by FTA.

## A FUNCTIONAL FAULT FACTOR ON DUCT SYSTEMS

It is possible to analyse with FTA functional fault factors on an air distribution system, which requires room pressure control. Three functional fault factors to be analysed and are proposed for commissioning.

(I) The air leakage of the duct system is large. When the actual air leakage exceeds estimated leakage, the supply fan capacity may not be enough and so that lowers the room pressure.

(II) The static pressure loss of the duct system is large. When the actual pressure loss exceeds estimated loss, the VAV may not adjust against the pressure loss so that lowers the room pressure.

(III) The VAV characteristic does not match the characteristic of the duct system. The VAV is characterised by the accuracy of its airflow velocity measurement and damper control system, thus its air flow tolerance. Basically this tolerance consists of the damper blade's airflow behaviour, the flow rate sensor's accuracy and the control unit's standard deviation.

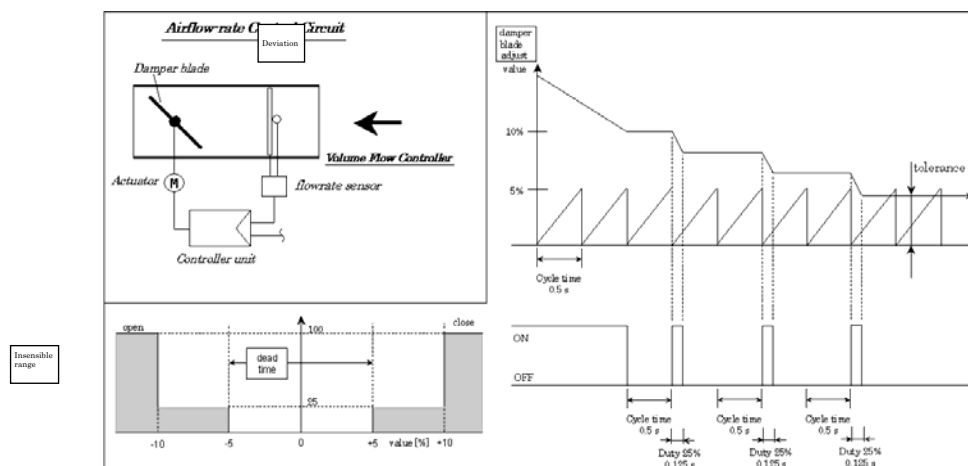


Figure 1. Example of VAV control unit's deviation

When the maximum/minimum air flow, in VAV's insensible range caused by VAV characteristic, does not meet duct pressure loss characteristic, it makes room relative pressure and air flow reverse. In the view of the abovementioned, the third object of duct system verification is (c) Verification of duct characteristics conformity with those of VAV.

## OUTLINE OF A DUCT SYSTEM FOR MODEL

The model system is a 100 percent fresh air system and the static pressure in the SA (Supply Air) duct behind the AHU is constant, adjusted by a fan inverter.

The SA is distributed to the three rooms A, B and C through VAV, VD and HEPA filter. For the system the VAV is used as constant air volume control device. Controlled room pressure generates airflow from Room B to A and B to C (i.e., pressure in Room B is (+ +), pressure in Room A is (+) and pressure in Room C is (+)).

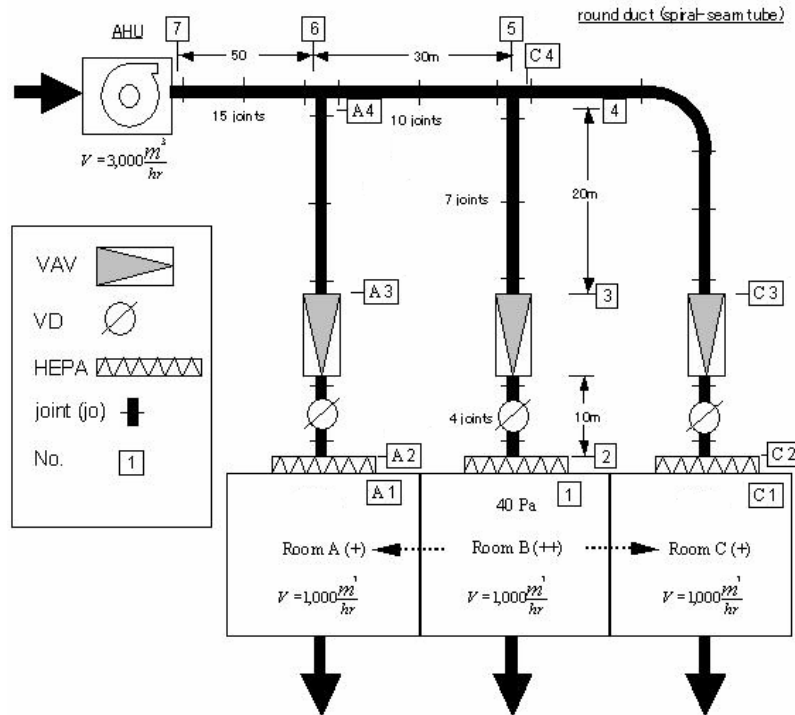


Figure 2. Duct system for model

Figure 2 shows the importance of exact pressure distribution. A pressure loss in Room B and an increase in Room A or C could effect a contamination of the air in Room B.

## BASICS OF AIR STATIC PRESSURE AND LEAKAGE MODEL

For the model, observe the leakage of the duct from AHU to diffuser. The basics of the duct air leakage calculation are empirical leakage diagrams (provided by the duct manufacturer) and related equations (technical literature). The duct leakage is defined as difference between  $\dot{V}_1$  and  $\dot{V}_5$  like shown in Figure 3.

The room leakage  $\dot{V}_4$  is assumed in the design stage with approximately one time room air change (assumed by authors experience). During commissioning  $\dot{V}_4$  has to be measured like shown in Figure 7. As the room leakage is not a subject of this paper, it is not amplified.

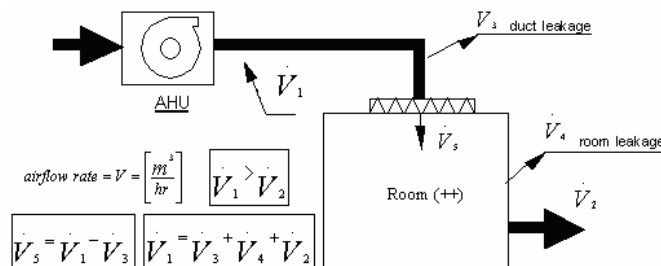


Figure 3. Air volume pattern for the positive pressure (++) room

The duct leakage is calculated from AHU to diffuser (HEPA filter) as shown in Figure 4 with the following models.

$$\dot{V} = 75 \cdot 10^{-8} \cdot p \quad (\text{for round spiral ducts}_{(1)}) \quad (1)$$

$$\dot{V} = 60 \cdot 10^{-5} \cdot p \quad (\text{for the joints of round spiral ducts}_{[1]}) \quad (2)$$

Where  $\dot{V}$  = leakage air volume per hour and meter [ $m^3/h/m$ ] and  $p$  = duct static pressure [ $Pa$ ]. The above equations to be applied to low pressure duct systems.

Equation (2) expresses the leakage per meter joint (e.g., one joint of a duct with a diameter of 0.2m has a joint length  $l_{joint} = 0.2m \cdot \pi = 0.628m$ )

The calculated duct leakage shown in Figure 4 has to be added to the total airflow requirement of the room. If it exceeds a number that is unacceptable for the design, the duct pressure loss calculation should be updated by adding the air leakage to the airflow in an iterative calculation.

The following equations are models to obtain the static pressure loss on the duct system.

$$\Delta p_{loss} = l_{duct} \cdot \text{duct friction} + \zeta \cdot p_{dyn} \quad (3)$$

$$\text{duct friction} = \frac{\lambda}{d_{duct}} \cdot p_{dyn} \quad (4)$$

$$\lambda = f(\text{Re}; \varepsilon; d_{duct}) \quad (5)$$

| No. | Duct elements  | Air Flow<br>(V)   | cross-section<br>(dA) | duct diameter<br>(dφ) | air velocity<br>(v) | p <sub>dynamic</sub><br>(p <sub>dyn</sub> ) | p <sub>static</sub><br>(p <sub>st</sub> ) | p <sub>total</sub><br>(p <sub>t</sub> ) | No. | ζ    | length<br>(l) | joints<br>(jo) | duct friction<br>(df) | Δp <sub>friction</sub><br>(Δp <sub>fr</sub> ) | Z  | Δp <sub>loss</sub><br>(Δp <sub>l</sub> ) | duct leakage<br>(V <sub>dl</sub> ) | %duct leakage<br>(%V <sub>dl</sub> ) | 2xduct leakage<br>(2V <sub>dl</sub> ) | 2% duct leakage<br>(2%V <sub>dl</sub> ) |
|-----|----------------|-------------------|-----------------------|-----------------------|---------------------|---|---|---|-----|------|---------------|----------------|-----------------------|---|----|--|------------------------------------|--------------------------------------|---------------------------------------|---|
|     |                | m <sup>3</sup> /h | m <sup>2</sup>        | m                     | m/s                 | Pa  | Pa  | Pa                                      |     |      | m             | quant          | Pa/m                  | Pa  | Pa | Pa                                       | m <sup>3</sup> /h                  | %                                    | m <sup>3</sup> /h                     | %                                       |
| 1   | Room 8<br>HEPA |                   |                       |                       |                     |   |   |   | 2   |      |               |                |                       |   |    | 250                                      |                                    |                                      |                                       |   |
| 2   | discharge      | 1000              | 0.07                  | 0.3                   | 3.9                 | 9   | 281                                       | 290                                     | 2   | 0.05 | 10            | 4              | 0.6                   | 6   | 0  | 6  | 0.672                              | 0.07                                 | 0.672                                 | 0.07                                    |
|     | VAR            |                   |                       | 0.2                   |                     |   |   | 296                                     | 3   |      |               |                |                       |   |    | 20                                       |                                    |                                      |                                       |   |
| 3   | induct         | 1000              | 0.07                  | 0.3                   | 3.9                 | 9   | 307                                       | 316                                     | 3   | 0.1  | 20            | 7              | 0.6                   | 12  | 1  | 13                                       | 1.308                              | 0.13                                 | 1.981                                 | 0.20                                    |
|     |                |                   |                       |                       |                     |   |   | 329                                     |     |      |               |                |                       |   |    |  |                                    |                                      |                                       |   |
| 4   | T-outlet       | 1000              | 0.07                  | 0.3                   | 3.9                 | 9   | 320                                       | 329                                     | 4   | 1.6  |               |                |                       | 0   | 15 | 15                                       | 0.000                              | 0.00                                 | 1.981                                 | 0.20                                    |
|     |                |                   |                       |                       |                     |   |   | 344                                     |     |      |               |                |                       |   |    |  |                                    |                                      |                                       |   |
| 5   | discharge      | 2000              | 0.10                  | 0.35                  | 5.8                 | 20  | 324                                       | 344                                     | 5   | 0.2  | 20            | 10             | 0.95                  | 28.5  | 4  | 33                                       | 2.493                              | 0.12                                 | 4.473                                 | 0.22                                    |
|     |                |                   |                       |                       |                     |   |   | 377                                     |     |      |               |                |                       |   |    |  |                                    |                                      |                                       |   |
| 6   | duct           | 3000              | 0.13                  | 0.4                   | 6.6                 | 26  | 350                                       | 377                                     | 6   |      | 50            | 15             | 0.95                  | 47.5  | 0  | 48                                       | 4.811                              | 0.16                                 | 9.285                                 | 0.31                                    |
|     |                |                   |                       |                       |                     |   |   | 424                                     |     |      |               |                |                       |   |    |  |                                    |                                      |                                       |   |
|     |                |                   |                       |                       |                     |   |   | 424                                     |     |      |               |                |                       |   |    |  |                                    |                                      | 9.3                                   | 0.31                                    |

Figure 4. Duct static pressure loss and air leakage example calculation

To determine the friction factor, the Moody Diagram is used. The friction factor is a subject of equation (6) and proportion of  $\varepsilon$  and  $d_{duct}$ .

$$\text{Re} = \frac{v \cdot d_{duct}}{\nu} \quad (6)$$

$\nu$  = viscosity [ $m^2/s$ ]       $\lambda$  = friction factor       $\zeta$  = C coefficient for fittings  
 $v$  = velocity [ $m/s$ ]       $\text{Re}$  = reynolds number       $p_{dyn}$  = dynamic pressure [ $Pa$ ]  
 $\varepsilon$  = roughness of duct material [ $m$ ]       $l_{duct}$  = length of the duct [ $m$ ]  
 $d_{duct}$  = hydraulic diameter of the duct [ $m$ ]

Figure 5 shows the pressure distribution in the ventilation system. The pressure loss of the installed system may vary from the designed pressure loss. The difference can be positive or negative.

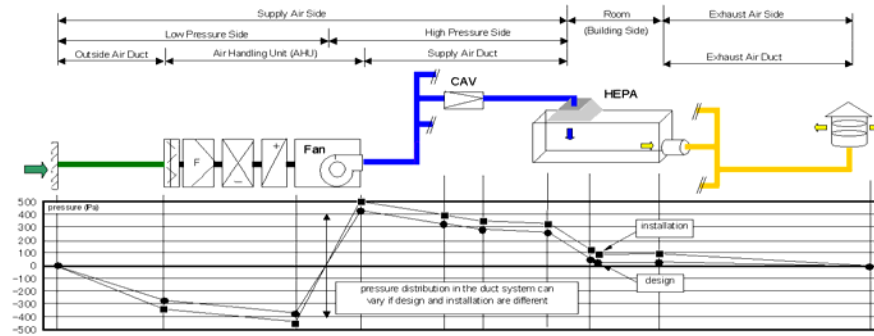


Figure 5. Pressure distribution in an air ventilation system

### COMMISSIONING PROCESS FOR THREE OBJECTS

Go through three Steps like shown in the flowchart (Figure 6) and explained as follows.

#### **Step I.** Verification of duct air tightness

Compare the estimated air leakage studied by the model with the actual leakage measured by a leakage measuring system like shown in Figure 7.

When the actual leakage exceeds the estimated air leakage, the ductwork must be adjusted or reworked.

Leakage on the air duct might be caused by:

- 1.) The leakage class of the installed duct type does not match the design. See for example HASS 010-2000<sub>[2]</sub>, Eurovent 2/2 or DIN 24194.
- 2.) The duct installation is poor.

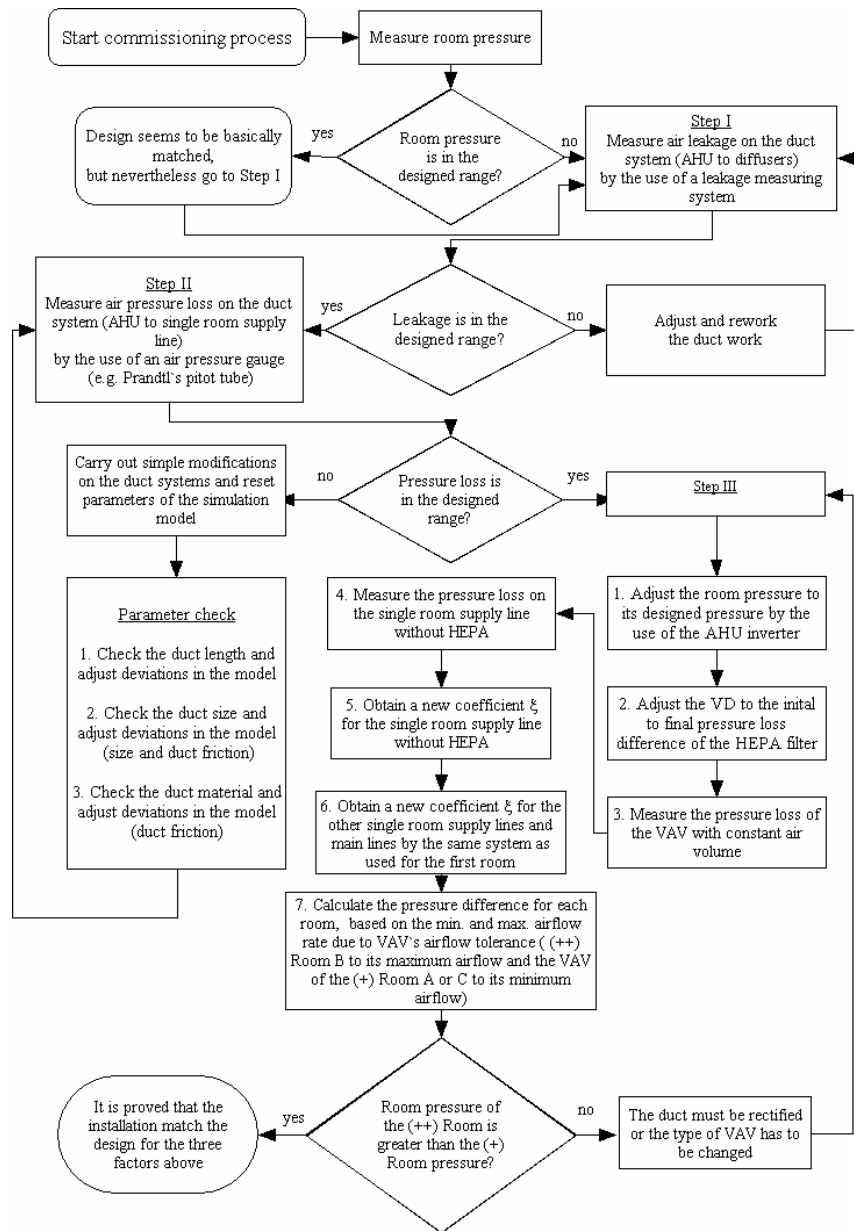


Figure 6. Flowchart on commissioning process of three objects

Figure 7 shows a performed duct and room leakage measurement of a clean room during commissioning process.

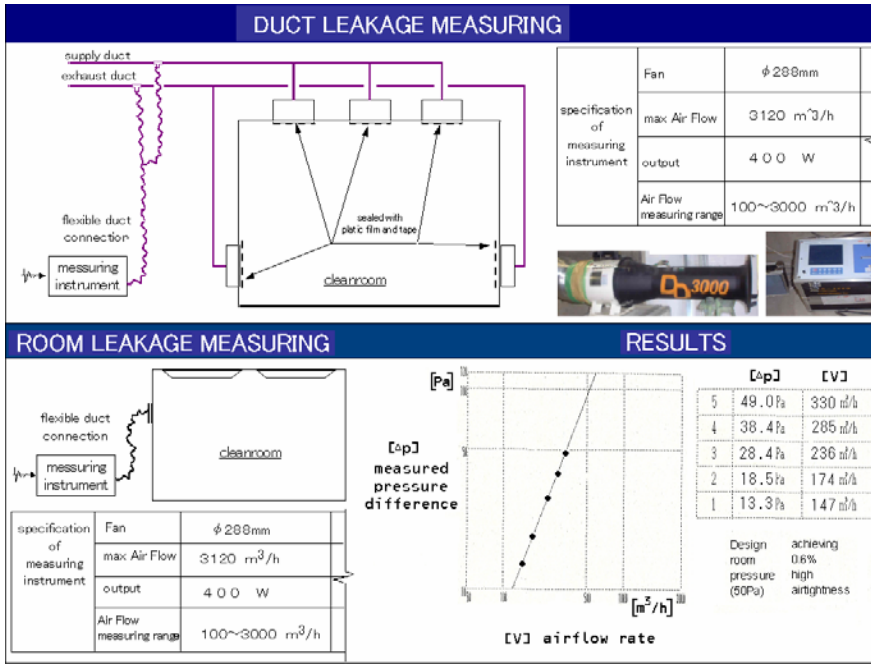


Figure 7. Duct and Room Leakage Measurement [3]

**Step II. Verification of static pressure loss on the duct**

Compare estimated static pressure studied by pressure distribution simulation model with measured static pressure at the numbered points shown in Figure 2 from AHU to VAV.

When the actual pressure loss exceeds the estimated air pressure loss and is difficult to be reduced by simple system modifications, the parameter of the simulation model needs to be reset to meet the measured data of the installed duct system. This is mainly a review on the duct friction (df).

Due to the affect shown in the equations (3) to (6), the following check should be carried out:

1.) Is the duct length ( $l_{duct}$ ) identical to the design?

If not, adjust the length in the model.

2.) Is the duct size ( $d_{duct}$ ) identical to the design?

3.) Is the duct material identical to the design?

If not, adjust the size and the duct friction in the model.

The influence by different roughness of designed material and the different C coefficients will be considered in step 3.

**Step III. Verification of duct characteristics conformity with those of VAV**

Simulate the duct pressure loss at the value of maximum/minimum flow rate within the tolerance from the set point of VAV, and analyse whether the room pressure kept as designed. In practice the steps as follows need to be carried out:

(1) At first, adjust supply air duct flow rate to the designed value by use of the AHU inverter.

(2) Simulate the pressure difference between the HEPA filter's initial and final pressure loss ( $\Delta p_{HEPA \text{ initial to final}}$ ) by the Volume Damper (VD). Measure the static pressure before ( $p_{VD\_in}$ ) and behind ( $p_{VD\_out}$ ) the VD to know the pressure difference of the VD ( $\Delta p_{VD}$ ). Then the VD to be adjusted in a condition, that its pressure loss is the same as the increase of initial to final pressure loss of the HEPA filter ( $\Delta p_{VD}$  to be  $\Delta p_{HEPA \text{ initial to final}}$ ).

(3) Next, measure the VAV's pressure loss ( $\Delta p_{VAV}$ ).

(4) Measure pressure at point no. 4 ( $p_4$ ) and point no. 2 ( $p_2$ ) of Figure 2. The total pressure loss will be

$$\Delta p_{loss \ 4 \ to \ 2} = p_4 - p_2 \quad (7)$$

(5) Obtain a new C coefficient  $\xi$ . Since this new coefficient is the combination of the C coefficient, a different roughness ( $\epsilon$ ) of the designed material and also the VAV's and VD's pressure loss characteristics, which are exponential mode to air velocity. The new symbol  $\xi$  (Xi) is chosen. With the combination of equation (3) and (4) this leads to

$$\Delta p_{loss} = l_{duct} \cdot duct \ friction + \xi \cdot p_{dyn} \quad (3)$$

$$duct \ friction = \frac{\lambda}{d_{duct}} \cdot p_{dyn} \quad (4)$$

$$\Delta p_{loss} = (l_{duct} \cdot \frac{\lambda}{d_{duct}} + \xi) \cdot p_{dyn} \quad (8)$$

$$\text{with } \xi = (l_{duct} \cdot \frac{\lambda}{d_{duct}} + \xi) \quad (9)$$

$$\Delta p_{loss} = \xi \cdot p_{dyn} \quad \Leftrightarrow \quad \xi = \Delta p_{loss} / p_{dyn} \quad (10)$$

These equations are for general use. For the ongoing calculation  $\xi_{4 \text{ to } 2}$  is the proportion of  $\Delta p_{loss \ 4 \text{ to } 2}$  to  $p_{dyn \ 4 \text{ to } 2}$ .

(6) Also obtain a new coefficient  $\xi$  (Xi) for Room A, Room C and the sections from No.7 to No.6 and No.6 to No.5 by using the same system then for Room B.

Now the duct system pressure loss model is ready for commissioning.

(7) Based on the minimum and maximum airflow rate due to VAV's airflow tolerance, calculate the pressure difference for each room. Study whether Room B be maintained at pressure (++)).

$$\text{requirement } \Delta p_{Room B} > \Delta p_{Room A \text{ or } C} \quad (11)$$

$$\text{when: } VAV_{Room B} = \max \text{ airflow} \quad (12)$$

$$\text{and } VAV_{Room A \text{ or } C} = \min \text{ airflow} \quad (13)$$

$$\text{If } \Delta p_{Room B} < \Delta p_{Room A \text{ or } C} \quad (14)$$

the duct should be rectified or the type of VAV has to be changed.

In practice compare the following by calculation:

$$\Delta p_{Room B} = p_7 - \Delta p_{loss \ 7 \text{ to } 6} - \Delta p_{loss \ 6 \text{ to } 5} - \Delta p_{loss \ 4 \text{ to } 1} \quad (15)$$

$$\text{with } \Delta p_{Room A} = p_7 - \Delta p_{loss \ 7 \text{ to } 6} - \Delta p_{loss \ A4 \text{ to } A1} \quad (16)$$

$$\text{and } \Delta p_{Room C} = p_7 - \Delta p_{loss \ 7 \text{ to } 6} - \Delta p_{loss \ 6 \text{ to } 5} - \Delta p_{loss \ C4 \text{ to } C1} \quad (17)$$

$$\text{where } \Delta p_{loss \ 7 \text{ to } 6} = \xi_{7 \text{ to } 6} \cdot p_{dyn \ 7 \text{ to } 6} \quad (18)$$

$$\Delta p_{loss \ 6 \text{ to } 5} = \xi_{6 \text{ to } 5} \cdot p_{dyn \ 6 \text{ to } 5} \quad (19)$$

$$\Delta p_{loss \ 4 \text{ to } 1} = \xi_{4 \text{ to } 2} \cdot p_{dyn \ 4 \text{ to } 2} + \Delta p_{HEPA \text{ initial max airflow}} \quad (20)$$

$$\Delta p_{loss \ A4 \text{ to } A1} = \xi_{A4 \text{ to } A2} \cdot p_{dyn \ A4 \text{ to } A2} + \Delta p_{HEPA \text{ initial min airflow}} \quad (21)$$

$$\Delta p_{loss \ C4 \text{ to } C1} = \xi_{C4 \text{ to } C2} \cdot p_{dyn \ C4 \text{ to } C2} + \Delta p_{HEPA \text{ initial min airflow}} \quad (22)$$

$$p_{dyn} = \frac{\rho_{air}}{2} \cdot v^2 \quad (23)$$

$$v = \frac{\dot{V}}{A_{duct}} \quad (24)$$

$$\dot{V}_{VAV_{Room B} = \max \text{ airflow}} = 1,000 \frac{m^3}{3600 s} + VAV \text{ flowrate tolerance} \quad (25)$$

$$\dot{V}_{VAV_{Room A \text{ or } C} = \min \text{ airflow}} = 1,000 \frac{m^3}{3600 s} - VAV \text{ flowrate tolerance} \quad (26)$$

$$\Delta p_{HEPA \text{ initial max airflow}} = f(\dot{V}_{VAV_{Room A \text{ or } C} = \max \text{ airflow}}) \quad (27)$$

$$\Delta p_{HEPA \text{ initial min airflow}} = f(\dot{V}_{VAV_{Room A \text{ or } C} = \min \text{ airflow}}) \quad (28)$$

Air velocity:  $v [m/s]$       Airflow rate:  $\dot{V} [m^3/s]$

Cross-section duct:  $A_{duct} [m^2]$       Density of air:  $\rho_{air} \approx 1.2 \frac{Kg}{m^3}$

For example, the flow-rate tolerance of a VAV is 7% at its designed airflow rate of 1,000 m<sup>3</sup>/h. Its max airflow would be 1,000 plus 7% = 1,070m<sup>3</sup>/h. Its min airflow would be 1,000 minus 7% = 930m<sup>3</sup>/h. The HEPA's initial pressure loss would increase 9 Pa and decrease 9 Pa respectively. Using the model with the design data, the result is a reverse airflow from room A (++) and C (++) to room B (+).

### CONCLUSIONS

This paper discussed commissioning methodology for simple duct system, dividing in three steps. Commissioning process for step I and II is well known matter. Step III clarifies small tolerance of VAV may affect final function of duct system and propose simple equation as a model.

Since the combination of the airflow rate deviation cannot be achieved intentionally on site, even though a room pressure measurement is conducted, it is just a single case based on combination of unidentified flow rate deviation.

As the example calculation demonstrates, the VAV's tolerance may have an influence on room pressure, and the proposed simple model can simulate by simple model without thousands of measurements. On site application is partially done in a pharmaceutical factory project (B building in Japan), the proposed commissioning model is appeared to be effective.

### NOMENCLATURE

|                      |   |
|----------------------|---|
| <i>AHU</i>           | Air Handling Unit   |
| <i>HEPA</i>          | High Efficiency Particulate Air-filter  |
| <i>SA</i>            | Supply Air  |
| <i>VAV</i>           | Variable Air Volume-Controller  |
| <i>VD</i>            | Volume Damper   |
| <i>(++) pressure</i> | positive pressure, higher than (+) pressure                                       |
| <i>(+) pressure</i>  | positive pressure, lower than (++) pressure, but higher than atmospheric pressure |

### REFERENCES

1. **Ikemoto H.**, Design of Duct - Riko Tosyo, 1981. - P.195.
2. **Heating, Air-Conditioning and Sanitary Standard**, Standard Specification for Air-Conditioning and Plumbing Works, Japan- HASS 010-2000. - P.101-105.
3. **Odajima T.**, Latest methods for facility design and construction for manufacture of sterile medicinal product, Ajinomoto Pharma Co., Ltd Saitama factory, - Interphex Japan 2004, Takenaka Corporation Japan, 2004
4. **TROX Technik.**, TROX Varycontrol VAV Terminal units, type TVS, - Gebr. Trox GmbH, Germany 1998. – 5/1.1/EN/1. – P.5.